Linear and Nonlinear Microwave Characterization of CVD-Grown Graphene Using CPW Structure

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Abstract: The linear and nonlinear microwave properties of chemical vapor deposition (CVD) grown graphene are characterized in this work by using a co-planar waveguide (CPW) structure. The intrinsic properties of the graphene are extracted and fitted with an equivalent circuit model. The nonlinear properties of the graphene are also measured and will be used for determining the thermal properties of graphene.
keywords: Graphene, De-embedding, Nonlinearity.

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Outline

- Introduction
- Motivation
- Test Fixture Design and Fabrication
- Experimental Characterization
- Conclusions

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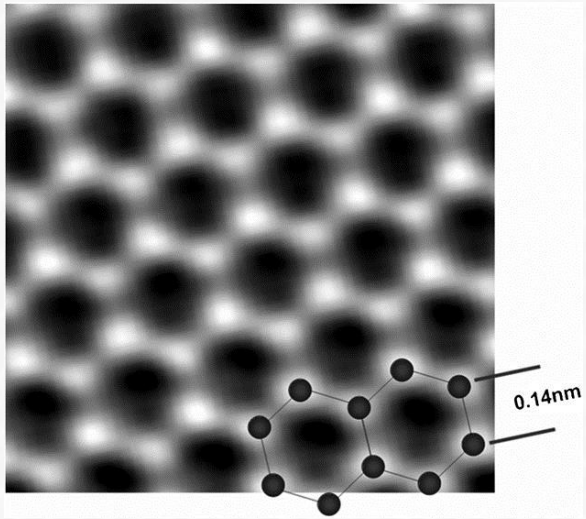
Graphene Properties



- Thinnest / strongest sheet material (5 times of steel and much lighter)
- Zero band gap semiconductor: conducts as best metals and **electrical properties can be modulated**
- High mobility ($\geq$ 100,000 cm^2/Vs)
  - Ballistic conduction 100's nm
  - High current density (~ 10^9 A/cm^2)
- Super heat conductor (~ 5 x 10^3 W/m.K)

Large-Area Graphene on Arbitrary Substrate

[1] M. S. Dresselhaus, "Graphene and Beyond: A Perspective," NSF Workshop, May 30, 2012

EM Applications

- THz (0.1-2.5 THz) and optical (188-222 THz) modulators [1,2]
- THz polarimeter (0.5-2.5 THz) and isolator at 20 GHz [3-5]
- Tunable THz absorbers [6]
- Near Infrared switch [7]
- Plasmonic cloak structure [8]
- Reconfigurable THz antenna [9, 10]

[1]Liu, M. et al. A graphene-based broadband optical modulator. Nature 474, 64-67 (2011).
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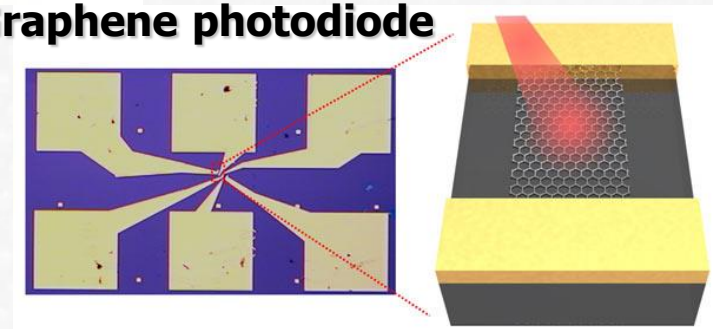
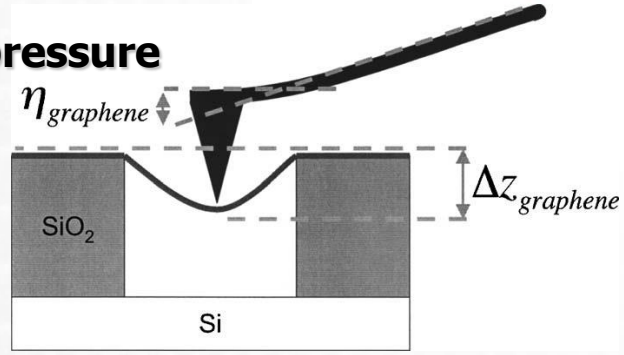
Other Applications

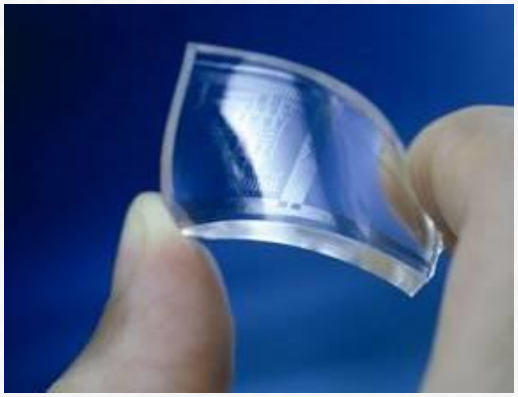
Graphene photodiode



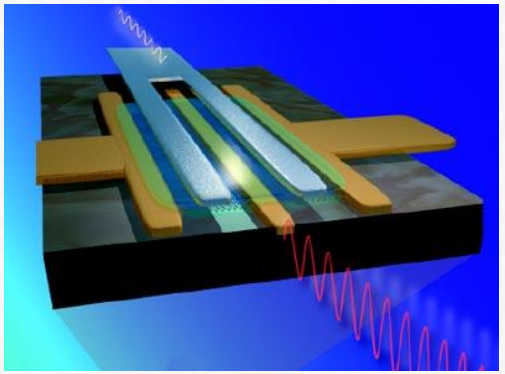
NEMS pressure sensor



Flexible LCD display



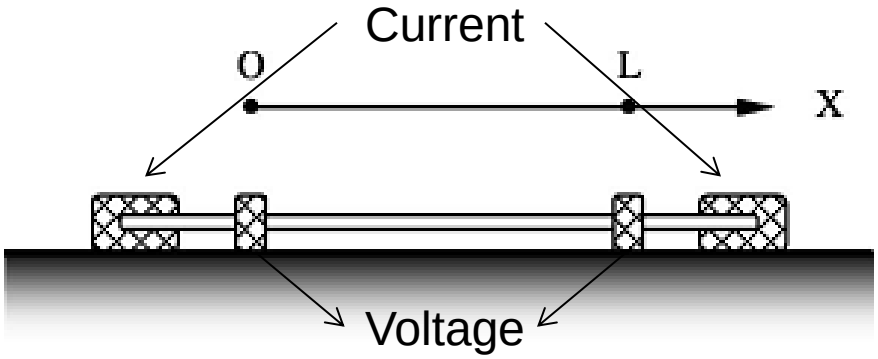
100 GHz Graphene transistor demonstrated



1. M. D. Stoller et. al., *Nano. Lett.* **8**, 3498 (2008)
2. I. W. Frank et. al., *J. Vac. Sci. Technol. B* **25**, 2558 (2007)

Motivation

- Excellent electrical, mechanical and thermal properties
  - Study of graphene σ will help towards potential EM applications
  - In addition to many free space characterizations
  - Experimental results inconsistent due to sample variations
  - **3-ω method used to characterize the heat capacity of graphene**



Original 3-ω structure for suspended wire

[1] L. Lu, W. Yi, and D. L. Zhang, "3ω method for specific heat and thermal conductivity measurements," Rev. Sci. Instrum. 72 , 2996 (2001).

Principle of 3-ω Method

- AC signal @ω flowing through the material
- The resistance changes with the variation of temperature
- Inducing AC signal @3ω across the structure

$$V_{3\omega} = I_{\omega} * \delta R_{2\omega}$$

$$\delta R_{2\omega} = \frac{\pi^2}{4} \frac{{I_{\omega}}^2 R R'}{\omega \rho C_p L S}$$

C_p: the heat capacity
ρ: the mass density
L: the length of sample
S: the cross section of the sample
R: the electric resistance
$R' = (dR/dT)$ around room temperature
$(= -R(\mu_c = 0)/T_0)$

Heat capacity can be derived from 3ω measurement

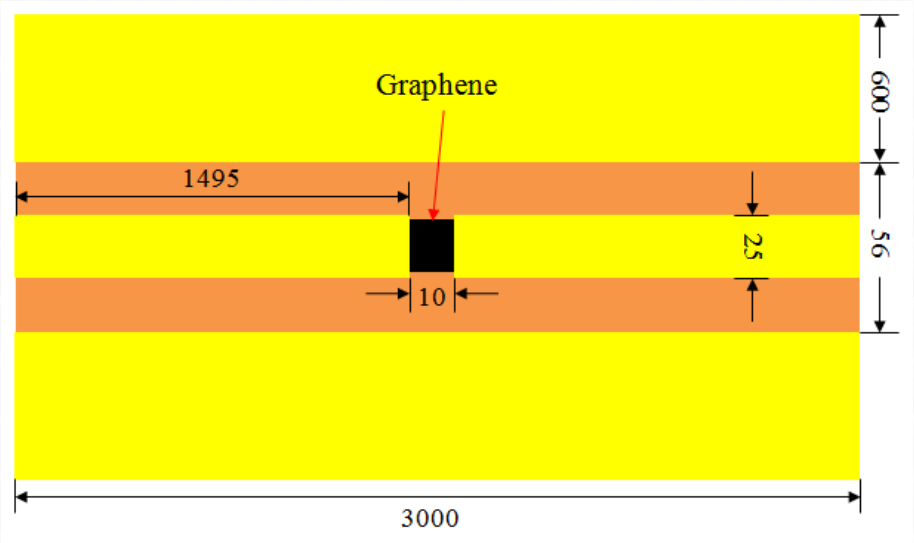
Challenge of Heat Capacity Measurement

- Previous work, measure long sample (e.g., nanotube) at low frequency

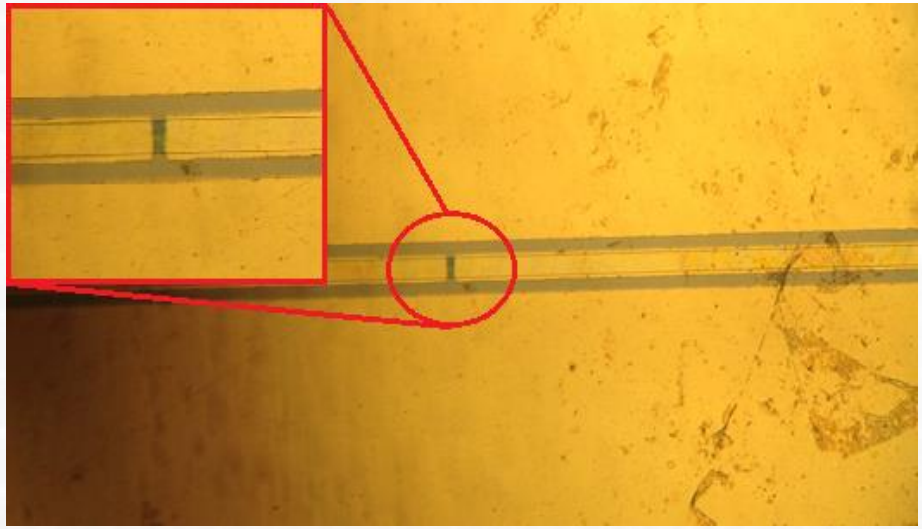
- In our work, measure short sample (e.g., graphene) at high frequency
  - mm-scale vs. μm-scale due to the fabrication limit
  - kHz range for long sample vs. GHz range for short sample

Circuit Design and Fabrication

- CPW structure designed with $Z_0 = 50\ \Omega$
- CVD SLG transferred onto high-ρ Si
  - using the PMMA transfer method



The dimension of the CPW structure (unit: μm)

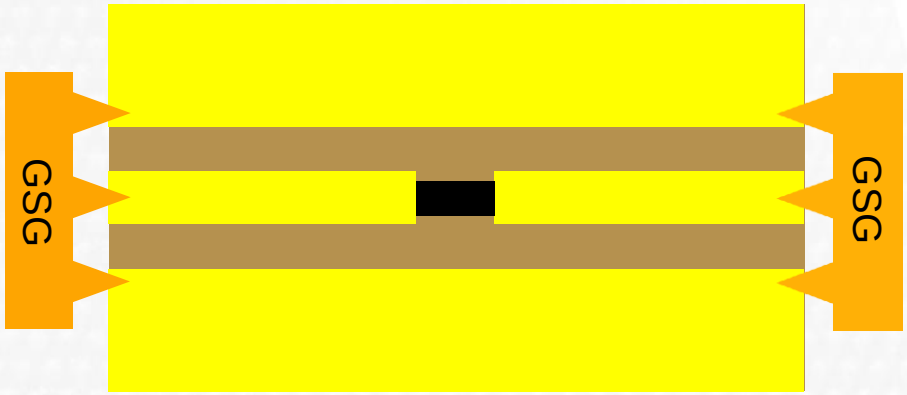


Microscope image of a fabricated graphene device

Experimental Characterization

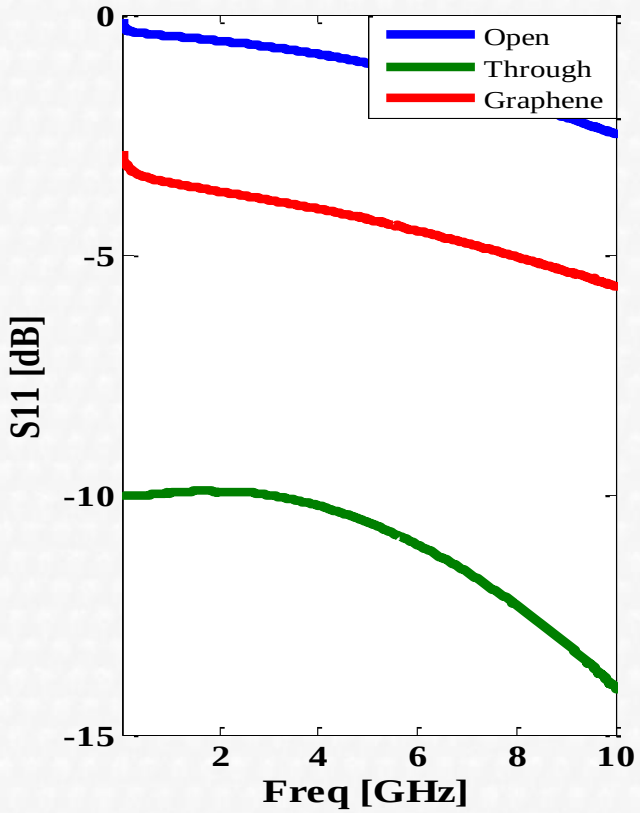
- Linear Characterization
  - On-wafer measurement
  - “Open” and “Through” structures as calibration
  - Equivalent circuit model for intrinsic properties extraction

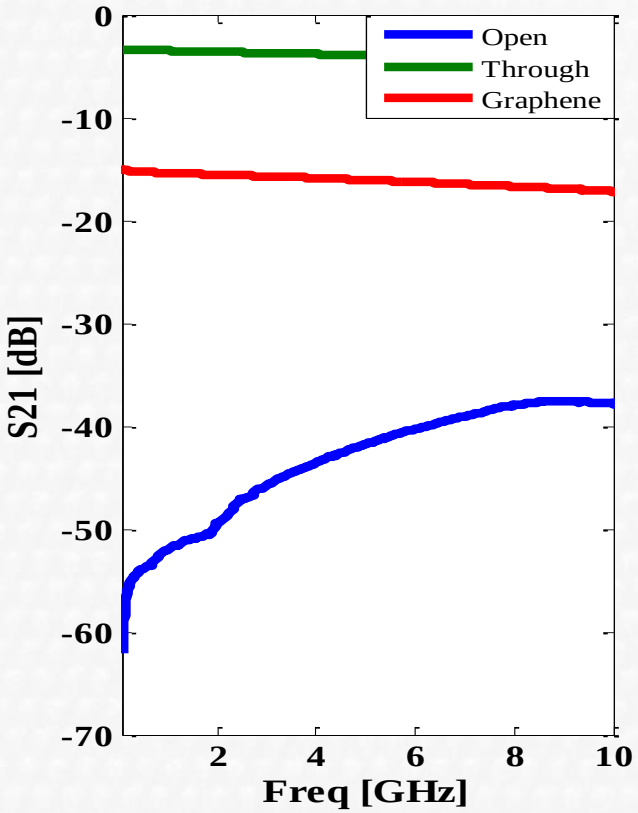
- Nonlinear Characterization
  - Harmonic measurement

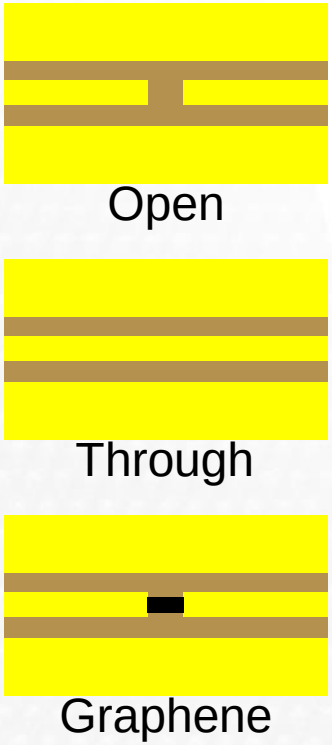


Measurement Results

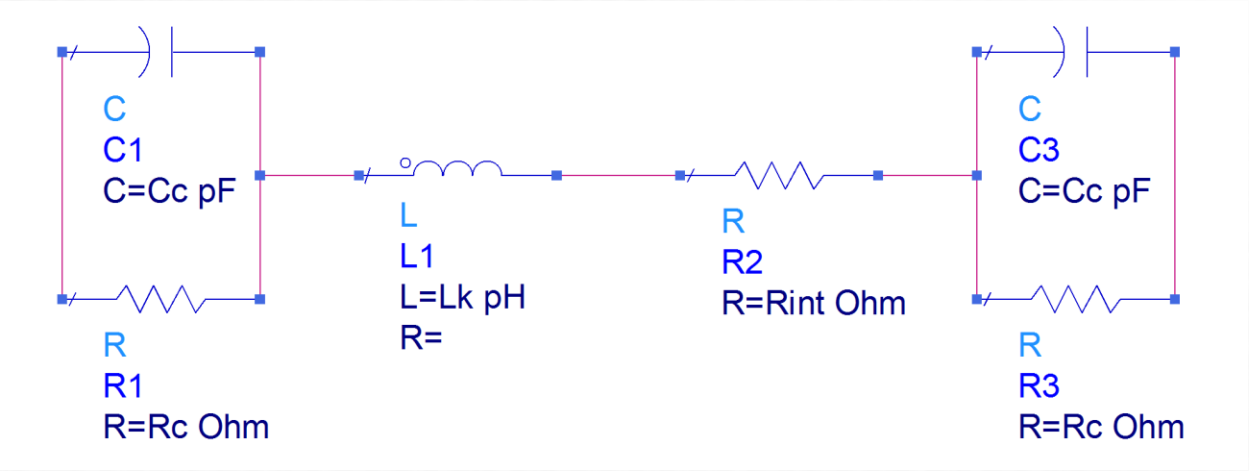
- Measured magnitude of transmission and reflection coefficient for graphene and calibration standards:







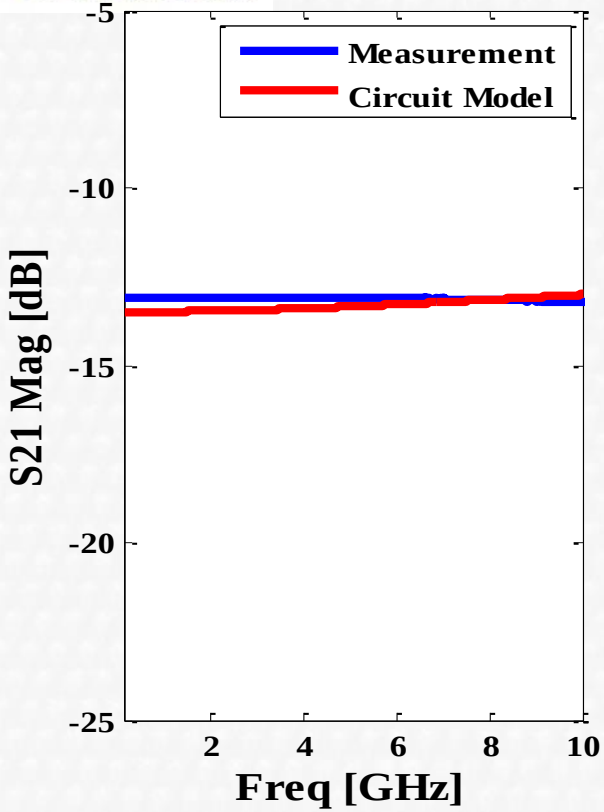
Equivalent Circuit Model

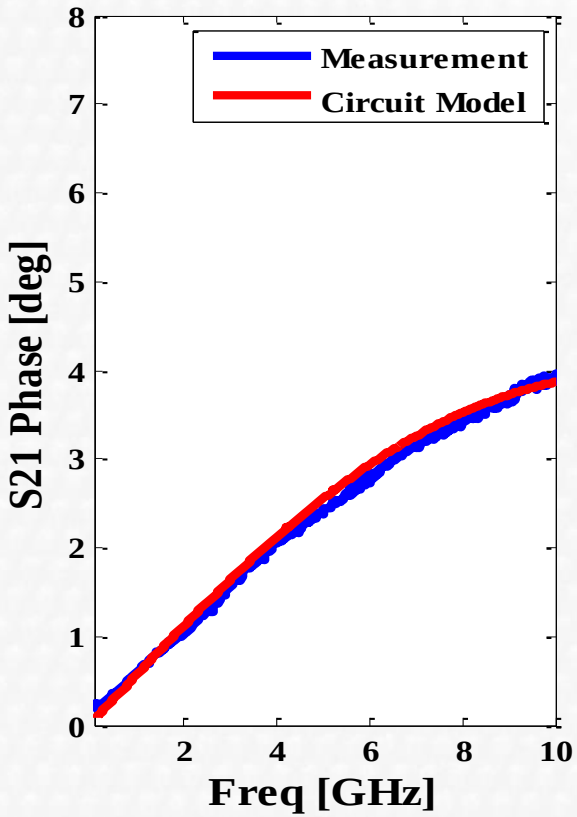


Equivalent circuit model of the intrinsic graphene after de-embedding

R_c – the contact resistance
C_c – the contact capacitance with electrodes
R_{int} – the intrinsic resistance
L_k – the equivalent inductance of graphene

Circuit Model Fitting and Comparison with Measurement





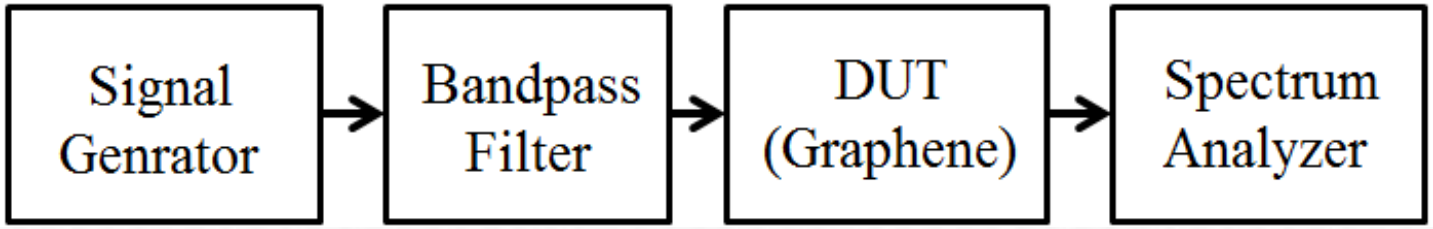
$$R_s = R_{int}\frac{W}{L} = R_{int}\frac{25\mu m}{10\mu m} = 682.34\ \Omega/\square$$

$$L_s = L_k\frac{W}{L} = L_k\frac{25\mu m}{10\mu m} = 0.558\ nH/\square$$

Rc [Ω]	Cc [pF]	Rint [Ω]	Lk [pH]
49.91	0.193	272.935	223.079

Nonlinear Characterization

- Exciting the device at f_0 from one port
- Measuring the $3f_0$ signal at the other port

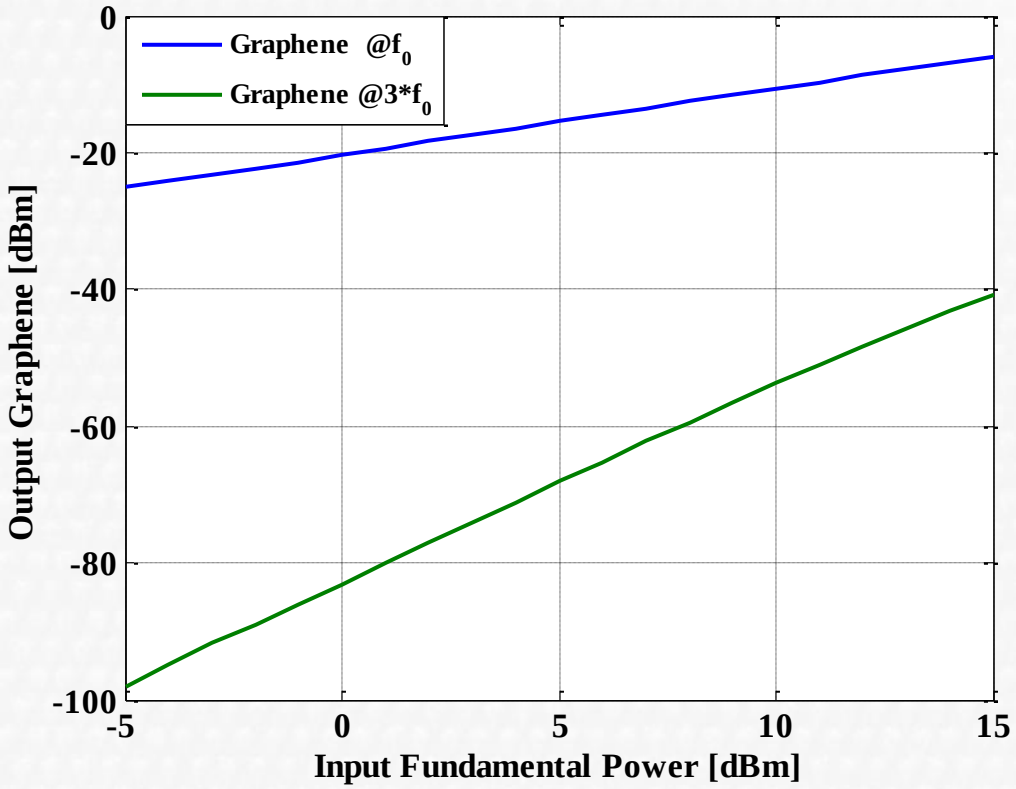


Scheme of graphene nonlinearity measurement setup

In experiment, the fundamental frequency is chosen at 1.5 GHz.

Measurement $3f_0$ Results

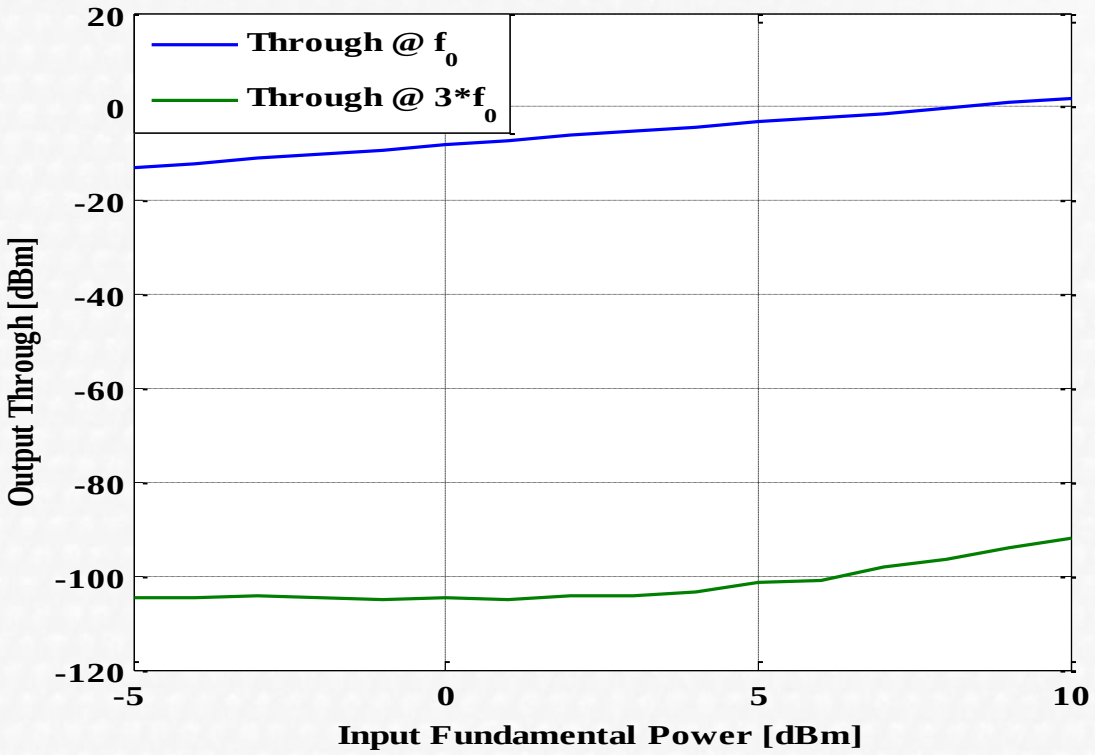
- Measured f_0 and $3f_0$ signals for graphene sample



Clear third harmonic for graphene sample

Measurement $3f_0$ Results

- Measured f_0 and $3f_0$ signals for through sample



No third harmonic for through sample

Conclusions

- Linear and nonlinear properties of graphene in CPW test figure are characterized
- Intrinsic linear graphene properties are extracted
  - Measured impedance (~680 Ω/sq & 0.56 nH/sq) reasonable
- Nonlinearity of graphene is investigated
  - Clear third harmonic signal seen
  - Goal is for graphene heat capacity extraction (suspended graphene is needed)

Future Work

- Investigate other nonlinear effects in graphene
- Extract the heat capacity of graphene
  - Using the extracted intrinsic circuit model parameters, together with the third harmonic results

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